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(54) Improved trench MOS gate device and method of producing the same

(57) A trench MOS gate device that comprises a trench whose floor and sidewalls include layers of dielectric material, having a controlled thickness dimension. These thickness dimensions are related by a controlled floor:sidewall layer thickness ratio, which is established by individually controlling the thickness of each of the floor and sidewall dielectric layers. This floor to sidewall layer thickness ratio is at least 1 to 1, and preferably at least 1.2 to 1. A process for forming a

trench MOS gate device comprises etching a trench in a silicon device wafer and forming layers of dielectric material on the trench floor and on the sidewalls, each layer having a controlled thickness dimension, related by a controlled floor to sidewall layer thickness ratio that is preferably at least 1 to 1. When silicon dioxide is employed as the dielectric material, the layers preferably comprise a composite of thermally grown and deposited silicon dioxide.

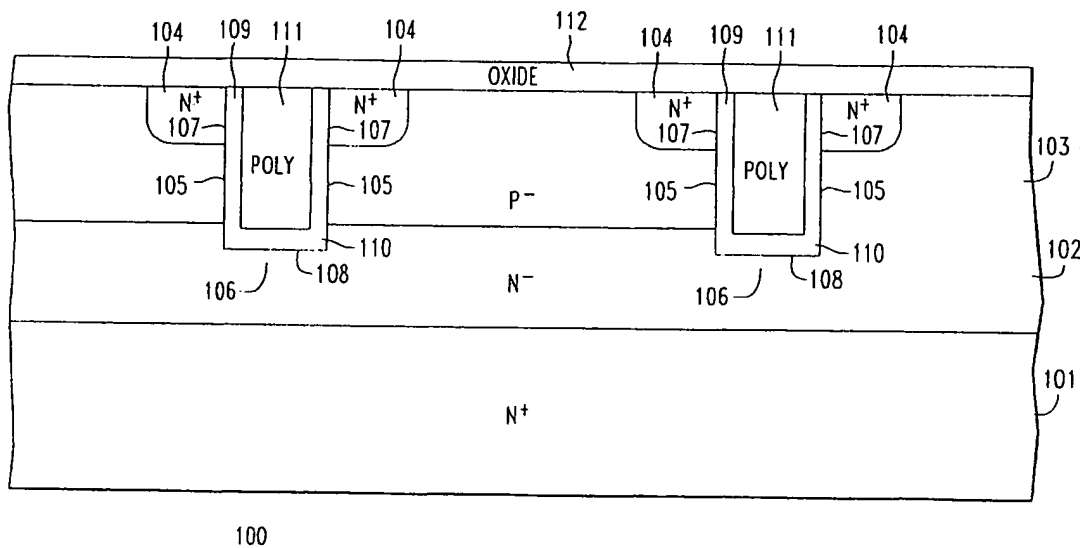


FIG. 1

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Description

The present invention relates to MOS devices and, more particularly, to a trench MOS gate device and a process for forming same.

An MOS transistor that includes a trench gate structure offers important advantages over a planar transistor for high current, low voltage switching applications. In the latter configuration, constriction occurs at high current flows, an effect that places substantial constraints on the design of a transistor intended for operation under such conditions.

A trench gate of a DMOS device typically includes a trench extending from the source to the drain and having sidewalls and a floor that are each lined with a layer of thermally grown silicon dioxide. The lined trench is filled with doped polysilicon. The structure of the trench gate allows less constricted current flow and, consequently, provides lower values of specific on-resistance. Furthermore, the trench gate makes possible a decreased cell pitch in an MOS channel extending along the vertical sidewalls of the trench from the bottom of the source across the body of the transistor to the drain below. Channel density is thereby increased, which reduces the contribution of the channel to on-resistance. The structure and performance of trench DMOS transistors are discussed in Bulucea and Rossen, "Trench DMOS Transistor Technology for High-Current (100 A Range) Switching" in *Solid-State Electronics*, 1991, Vol. 34, No. 5, pg. 493-507. In addition to their utility in DMOS devices, trench gates are also advantageously employed in insulated gate bipolar transistors (IGBTs), MOS-controlled thyristors (MCTs), and other MOS gated device structures.

Trenches lined with oxide dielectric and filled with polysilicon as a means of providing lateral isolation for component islands situated within the trench regions are disclosed in specifications of U.S. Patent Nos. 5,196,373 and 5,248,894. A preferred method of forming the dielectric for this purpose is conventional thermal oxidation.

Thermal oxidation to produce silicon dioxide for isolation of component islands does not require the control of oxide layer thickness provided by the device and process of the present invention. The dielectric used for isolation is very thick, often thicker than 10,000 angstroms. In this thickness range, the oxide grows according to a parabolic growth rule that produces the same growth rate on all crystal surfaces rather than by the orientation dependent linear growth rate that applies to the hundreds of angstroms thickness range relevant for gate oxides. Consequently, thermally grown oxides for isolation purposes have essentially the same thickness on all surfaces.

To minimize oxidation induced stress, a thin, approximately 100-angstrom thick thermal oxide layer is sometimes grown to cover an island surface. This thin oxide layer is then covered with a thick deposited oxide

layer of about 10,000 angstroms to provide the required isolation. In such instances, the isolation layer consists almost entirely of deposited oxide. This layer must be thick enough to ensure that average capacitance is low and that the oxide rupture voltage is higher than the maximum voltage to be isolated. However, there are no minimum thickness or uniformity constraints for oxide layers intended for isolation of component islands.

Although the trench gate structure is beneficial for the operation of a transistor at higher currents, its performance can be degraded by the formation of a gate-to-drain capacitance across the dielectric material in the bottom of the trench. Furthermore, the bottom corners of the trench can cause concentration of an electric field when the DMOS is reverse biased, resulting in reduced breakdown voltage. These effects can be mitigated by beneficially controlling the formation of the dielectric layers on the sidewalls and floor of the gate trench, which is provided by the present invention.

The present invention includes a trench MOS gate comprising, a trench having a floor and sidewalls, said floor and said sidewalls comprising a layer of a dielectric material, said floor layer and said sidewall layers each having a substantially uniform controlled thickness dimension, characterized in that said substantially uniform thickness dimensions are related by a controlled floor to sidewall layer thickness ratio, said ratio being established by individually controlling the substantially uniform thickness of each of said floor and sidewall layers.

The invention also includes a process for forming an improved trench MOS gate device comprising the steps of, forming a trench in a silicon device wafer, said trench having a floor and sidewalls, forming a layer of dielectric material on each of said floor and said sidewalls, said floor layer and said sidewall layers each having a substantially uniform controlled thickness dimension, said substantially uniform thickness dimensions being related by a controlled floor to sidewall layer thickness ratio, said ratio being controlled by individually controlling the substantially uniform thickness of each of said floor and sidewall layers, filling said trench containing said layers of dielectric material with polysilicon, applying an insulator over said polysilicon, so as to form a trench gate, and forming a patterned electrically conducting metallic interconnect on said trench gate.

Conveniently, a trench MOS gate device comprises a trench whose floor and sidewalls include layers of dielectric material, the layers each having a controlled thickness dimension. These thickness dimensions are related by a controlled floor: sidewall layer thickness ratio, which is established by individually controlling the thickness of each of the floor and sidewall dielectric layers. This floor to sidewall layer thickness ratio is preferably at least 1 to 1, more preferably at least 1.2 to 1.

Advantageously the process for forming a trench MOS gate device comprises etching a trench in a silicon device wafer and forming layers of dielectric material on

the trench floor and on the sidewalls, each layer having a controlled thickness dimension. The thickness dimensions are related by a controlled floor to sidewall layer thickness ratio that is preferably at least 1 to 1. When silicon dioxide is employed as the dielectric material, the layers preferably comprise a composite of thermally grown and deposited silicon dioxide.

The trench containing the dielectric layers is filled with polysilicon, and an insulator layer is formed over the polysilicon, thereby forming a trench gate. A patterned electrically conducting metallic interconnect is formed over the trench gate.

The trench MOS gate device includes a trench gate having a trench provided with layers of dielectric material of an advantageously controlled thickness ratio on the floor and the sidewalls, which reduces the damage caused by undesirable parasitic effects.

The invention will now be described by way of example with reference to the accompanying drawings in which:

FIG. 1 is a schematic representation of a trench gate structure of a DMOS transistor of the present invention.

FIG. 2 schematically depicts a process embodiment of the invention.

FIG. 3 is a schematic representation of a further process embodiment of the invention.

FIG. 4 schematically represents a trench gate structure of an IGBT of the invention.

FIG. 5 schematically depicts a trench gate structure for an MCT of the invention.

The previously described effects that degrade the performance of a trench DMOS transistor can be diminished by increasing the thickness of the silicon dioxide layer on the floor of the gate trench. However, there is a design conflict between the requirements for thick floor oxide to reduce parasitic effects and for thin oxide on the sidewalls of the trench to reduce channel resistance. This conflict is compounded when the conventional thermal oxidation process is used to form channel oxide on silicon substrate having the usual (100) crystal orientation. The thermal oxide grows relatively slowly on the (100) surface on the trench floor and more rapidly on other surfaces such as the (110) surfaces that form the trench sidewalls. As a result, the thermally grown oxide is thicker on the sidewalls than on the floor of the trench. Thus, for example, if a 500-angstrom thick layer of oxide were grown thermally on (110) trench sidewalls, the thickness of the simultaneously grown trench floor oxide layer would be only 355 angstroms because of the slower growth rate on the (100) surface.

If there are multiple crystal orientations for the sidewalls, as can occur when the common hexagon geometry is used for the trench pattern, thermally grown oxide will form layers of different thicknesses on sidewalls having different crystalline orientations. Channel resistance will be higher for the channel segments with thicker oxide, resulting in nonuniform current distribution

among the channel segments. This is another undesirable effect of the crystal orientation-dependent growth rate of the gate oxide.

The problems described above can be substantially diminished by using, in accordance with a preferred embodiment of the present invention, a composite oxide forming process for the trench gate. A first portion of the gate oxide is formed by thermal oxidation to achieve a low interface state density. The rest of the gate oxide is formed by chemical vapor deposition, which has a higher deposition rate on horizontal surfaces (such as the trench floor) than it does on vertical surfaces (such as the sidewalls). The faster deposition rate on horizontal surfaces compensates for the slower thermal oxide growth rate on those surfaces so that the composite oxide layer can be thicker on the floor than on the sidewalls.

A system useful for depositing gate oxide in accordance with the present invention employs a Novellus Concept 1 dielectric deposition apparatus, available from Novellus Corp. Such systems can deposit oxide by plasma CVD at a deposition rate ratio of about 2 to 1 on horizontal versus vertical surfaces. A ratio of greater than 1.5 to 1 is preferred.

Thus, a composite oxide having a sidewall total layer thickness of 500 angstroms may be formed on (110) trench sidewalls and (100) trench bottoms as follows: a 250-angstrom thermal oxide layer is grown on the trench sidewalls, along with a simultaneously grown 177-angstrom layer on the trench floor. A 250-angstrom layer of oxide is deposited on the sidewalls over the grown oxide, while a 500-angstrom-thick oxide layer is simultaneously deposited on the floor of the trench. The result of this composite gate oxide formation process is a 500-angstrom thick sidewall oxide layer and a 677-angstrom thick floor oxide layer. This produces the desirable result of thicker floor oxide to suppress parasitic features together with thinner sidewall oxide to minimize channel resistance, a result opposite to that obtained with a conventional dielectric-forming growth process, in which the sidewall oxide is thicker than the floor oxide.

The ratio of floor to sidewall oxide layer thicknesses can be adjusted over a wide range by adjusting the ratio of the thickness of the thermal to the deposited oxide. Using the process of the invention, the performance of a device can be optimized to a degree not possible using the conventional thermal oxidation process.

FIG. 1 schematically depicts a trench gate structure 100 for a DMOS transistor. Substrate 101 is an N⁺ silicon wafer on which is grown an N⁻ layer that provides a drain region 102. A P⁻ body region 103 is formed by doping, and N⁺ source regions 104 are formed in the body region 103 by masked ion implant. The difference between the body region 103 and the source region 104 diffusions defines the length of the channels 105.

Trenches 106 formed by patterned etching extend through portions of source regions 104 and body region 103 into drain region 102. Trenches 106 have sidewalls

107 and a floor 108. Sidewalls 107 and floor 108 each include layers 109 and 110, respectively, of silicon dioxide. The thickness of floor layer 110 is greater than that of sidewall layers 109. Layers 109 and 110 comprise a composite of thermally grown and deposited silicon oxide. Trenches 106 further contain highly doped polysilicon 111. An insulator layer 112 is formed over the polysilicon 111, which forms a gate between the source regions 104 and the drain region 102. The DMOS transistor of the invention is obtained from the trench gate structure 100 by forming contact apertures, interconnect metal, and a patterned dielectric protection layer over the metal, all not shown in FIG. 1.

In a preferred embodiment, the composite oxide contained in layers 109 and 110 comprises thermally grown silicon dioxide, produced by the reaction of silicon in an oxygen atmosphere, and deposited silicon dioxide, obtained by deposition of the reaction product of a volatile silicon-containing compound. Also in a preferred embodiment, the thickness of the floor layer 110, which may be in the range of about 300 to 3,000 angstroms, is greater than that of the sidewall layers 109, which may be in the range of 200 to 1,500 angstroms.

For low-voltage applications, it is desirable that the perimeter area ratio of the individual small transistors within a switching device be maximized in order to achieve minimum specific on-resistance. An important factor in attaining this objective is the gate topology of the device. The trench 106 included in a transistor may have an open-cell stripe topology or, preferably, a closed-cell cellular topology. Furthermore, the cellular topology of the trench 106 may have a square or, more preferably, a hexagonal configuration.

A process sequence useful to make a trench gate device for a DMOS transistor is illustrated in FIGS. 2A-G, which are not to scale.

The process begins with a silicon wafer 200 having an N⁺ layer 201 of (100) crystal orientation. An N⁻ silicon layer that provides a drain region 202 is grown on layer 201 using conventional epitaxial growth methods (FIG. 2A). The thickness and resistivity of the layer 202 are chosen to support the desired breakdown voltage while minimizing the on-resistance.

P⁺ body contacts 203 are optionally formed by masked ion implant and diffusion into selected areas of the wafer surface to act as low resistance body contacts (FIG. 2B). The body contacts 203 may optionally be formed later in the process or omitted.

A P⁻ body region 204 that overlaps the P⁺ body contacts 203 is formed (FIG. 2C). The doping profile of the body region 204 is chosen such that the desired threshold voltage will be obtained after the source and trench gates have been formed in the body. The depth of the body junction depth is about 2 microns.

N⁺ source regions 205 are formed in the body region 204 by masked ion implant such that they abut the body contacts 203 (FIG. 2D). The depth of the source region 205 is conveniently about 1 micron and is chosen

to give the desired channel length. The channel length, which is the difference between the depths of the body and source diffusions, is about 1 micron.

The trench pattern is formed in a suitable mask, and a trench 206 is etched through the exposed portions of source regions 205 and body region 204 into the underlying drain region 202 by reactive ion etching (RIE) (FIG. 2E).

The composite gate oxide is formed from thermally grown and deposited oxide on the exposed sidewalls and bottom of the trench, providing sidewall oxide layers 207 and bottom oxide layer 208. Preferably, this is carried out as previously described in this disclosure. After gate oxide formation, the remainder of the trench 206 is filled with polysilicon 209, and the polysilicon 209 is planarized by, for example, chemical-mechanical planarization (FIG. 2F).

The device fabrication is completed by forming an oxide insulator 210 over the gate polysilicon 209; forming contact apertures through the insulator to source, body contacts, and gate regions (not shown); applying a patterned electrically conducting metallic interconnect 211; and applying a dielectric protection layer 212 over the interconnect 211 (FIG. 2G).

Drain body junction breakdown maximization structures, which are not shown because they do not appear in the interior cellular part of the device, may be formed around the perimeter of the device.

The thermally grown portion of the composite gate oxide may, for example, be grown in O₂ at 900°C to a thickness of 175 angstroms on (100) crystal surfaces. A chlorine containing compound such as HCl may be included in the oxidizing atmosphere to remove metallic impurities.

The deposited portion of the composite oxide may be formed using a Novellus plasma CVD deposition system to a thickness, for example, of 500 angstroms on horizontal surfaces. O₂ and tetraethoxysilane (TEOS) source gases may be employed at a deposition temperature of about 400°C. The deposited oxide may be densified after deposition by annealing it in a diffusion furnace at 950°C in a nitrogen atmosphere that optionally contains a small oxygen concentration.

Another embodiment of the process of the invention that produces a thicker layer of oxide on the bottom than on the sidewalls in a trench gate structure is illustrated in FIGS. 3A-C, which are not to scale. The process is the same through the trench etch step as in the previously depicted process (FIGS. 2A-E).

After trench etch, a first gate oxide layer 301 covering all surfaces, both horizontal and vertical, is thermally grown to a sidewall thickness of, for example, 700 angstroms. A silicon nitride layer 302 about 1000 angstroms thick is deposited over the oxide layer 301 by LPCVD (FIG. 3A).

The portions of the nitride layer 302 in the bottoms of the trenches and also on the wafer top surface is removed by a nonmasked anisotropic reactive ion etch

(FIG. 3B), which attacks only material on horizontal surfaces. These surfaces are perpendicular to the direction of flight of the etch ions in the etch chamber.

A layer 303 comprising a second portion of gate oxide is then grown to provide a total thickness of, for example, 1000 angstroms on the surfaces not covered by nitride, including the trench bottom. The residual vertical nitride layer 302 protects the trench sidewalls from oxidation in the well known local oxidation process. The residual nitride layer 302 is preferably stripped after the formation of the oxide layer 303. This leaves the trench 206 with a 700-angstrom layer of oxide provided by layer 301 on the sidewalls and a desirably thicker 1000-angstrom layer of oxide provided by layers 301 and 303 together on its bottom (FIG. 3C). The trench 206 is filled with doped polysilicon, and the construction of the transistor is completed as illustrated by FIGS. 2F-G.

The trench gate oxide, which is preferably a composite of thermally grown and deposited oxide, in the device and process of the present invention is sufficiently thin to provide low on-resistance and has constant thickness on all sidewalls to provide equal current flow on the sidewall surfaces. Its interface charge density is low enough to provide low and controlled threshold voltage, and its floor layer thickness is sufficient to minimize capacitance and provide required oxide and junction breakdown.

FIG. 4 is a schematic representation of another embodiment a trench gate structure 400 for an insulated gate bipolar transistor (IGBT). Structure 400 includes a P⁺ type substrate 401, an N⁺ typed epitaxial layer 402, and body 403. The substrate 401 is the anode of the IGBT. The lightly doped layer 402 is a drift layer that supports high voltage when the device is off. The remaining components in structure 400 are as described for structure 100 of FIG. 1. The thickness of oxide layers 109 and 110 on sidewalls 107 and floor 108, respectively, of trenches 106 of structure 100 are advantageously controlled, as described for structure 100.

FIG. 5 schematically illustrates, as a further embodiment, a trench gate structure 500 in a P type MOS controlled thyristor (MCT). This structure includes an N⁺ substrate 501, on which is grown a P⁺ epitaxial layer 502. Structure 500 further comprises N type drift region 503, a P type body 504, and a P⁺ anode region 505. Substrate 501 provides the cathode region. Analogous gate structures useful for N type MCTs can also be constructed, in which case the conductivity type of all regions would be opposite to those depicted for structure 500. An insulator layer 506 is formed over polysilicon 111. The other components depicted in structure 500 are as described for structure 100 of FIG. 1. As with the previously described embodiments, the oxide layers 109 and 110 of structure 500 are characterized by a beneficially controlled thickness ratio.

Process sequences analogous to those illustrated in FIGS. 2A-G and 3A-C for a DMOS transistor gate device are employed to form other embodiments of the

present invention, wherein the thickness ratio of the trench floor and sidewalls is controlled.

A trench MOS gate device that comprises a trench whose floor and sidewalls include layers of dielectric material, having a controlled thickness dimension. These thickness dimensions are related by a controlled floor: sidewall layer thickness ratio, which is established by individually controlling the thickness of each of the floor and sidewall dielectric layers. This floor to sidewall layer thickness ratio is at least 1 to 1, and preferably at least 1.2 to 1. A process for forming a trench MOS gate device comprises etching a trench in a silicon device wafer and forming layers of dielectric material on the trench floor and on the sidewalls, each layer having a controlled thickness dimension, related by a controlled floor to sidewall layer thickness ratio that is preferably at least 1 to 1. When silicon dioxide is employed as the dielectric material, the layers preferably comprise a composite of thermally grown and deposited silicon dioxide.

Claims

1. A trench MOS gate device comprising, a trench having a floor and sidewalls, said floor and said sidewalls comprising a layer of a dielectric material, said floor layer and said sidewall layers each having a controlled thickness dimension, characterized in that said substantially uniform thickness dimensions are related by a controlled floor to sidewall layer thickness ratio, said ratio being established by individually controlling the substantially uniform thickness of each of said floor and sidewall layers.
2. A trench MOS gate device as claimed in claim 1, wherein said dielectric material comprises silicon dioxide.
3. A trench MOS gate device as claimed in claims 1 or 2, characterized in that said floor to sidewall layer thickness ratio is at least 1 to 1, preferably said thickness ratio is at least 1.2 to 1, and said floor layer of silicon dioxide has a thickness of 300 to 3,000 angstroms, or preferably 200 to 1500 angstroms.
4. A trench MOS gate device as claimed in any one of claims 1 to 3 characterized in that said trench gate comprises doped polysilicon disposed within said trench, said trench has an open-cell, stripe topology, or a closed-cell, cellular topology.
5. A trench MOS gate device as claimed in claim 4, characterized in that said trench has a substantially square or hexagonal cellular topology.
6. A semiconductor device including the trench MOS gate device of any one of claims 1 to 5.

7. A semiconductor device as claimed in claim 6 characterized by a DMOS transistor, or an insulated gate bipolar transistor, or a MOS-controlled thyristor.

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8. A trench MOS gate device as claimed in any one of claims 1 to 5, characterized in that said floor layer and said sidewall layers each comprise a composite of thermally grown silicon dioxide and deposited silicon dioxide, in which said thermally grown silicon dioxide comprises a product of reaction of silicon in an oxygen-containing atmosphere.

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9. A trench MOS gate device as claimed in claim 8, characterized in that said deposited silicon dioxide comprises a chemical vapor deposited reaction product of a volatile silicon-containing compound.

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10. A process for forming an improved trench MOS gate device comprising the steps of, forming a trench in a silicon device wafer, said trench having a floor and sidewalls, forming a layer of dielectric material on each of said floor and said sidewalls, said floor layer and said sidewall layers each having a substantially uniform controlled thickness dimension, said substantially uniform thickness dimensions being related by a controlled floor to sidewall layer thickness ratio, said ratio being controlled by individually controlling the substantially uniform thickness of each of said floor and sidewall layers, filling said trench containing said layers of dielectric material with polysilicon, applying an insulator over said polysilicon, so as to form a trench gate, and forming a patterned electrically conducting metallic interconnect on said trench gate.

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11. A process as claimed in claim 10 characterized by a dielectric protection layer over said metallic interconnect, in which said layer of dielectric material in said trench comprises silicon dioxide, with said floor:sidewall layer thickness ratio is at least 1 to 1, or preferably said ratio is at least 1.2 to 1.

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12. A process as claimed in claim 10, characterized by said floor layer of silicon dioxide has a thickness of 300 to 3,000 angstroms, and preferably said sidewall layers of silicon dioxide have a thickness of 200 to 1,500 angstroms, and said floor layer and said sidewall layers each comprise a composite of thermally grown silicon dioxide and deposited silicon dioxide, and said thermally grown silicon dioxide comprises the product of reaction of silicon in an oxygen-containing atmosphere, with said reaction is carried out at a temperature of 700° to 1050°C, or is carried out at a preferred temperature of about 300°C to 800°C.

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13. A process as claimed in any one of claims 10, 11 or

12 characterized by following said depositing annealing said deposited silicon dioxide, and removing from said sidewalls the layer of silicon nitride.

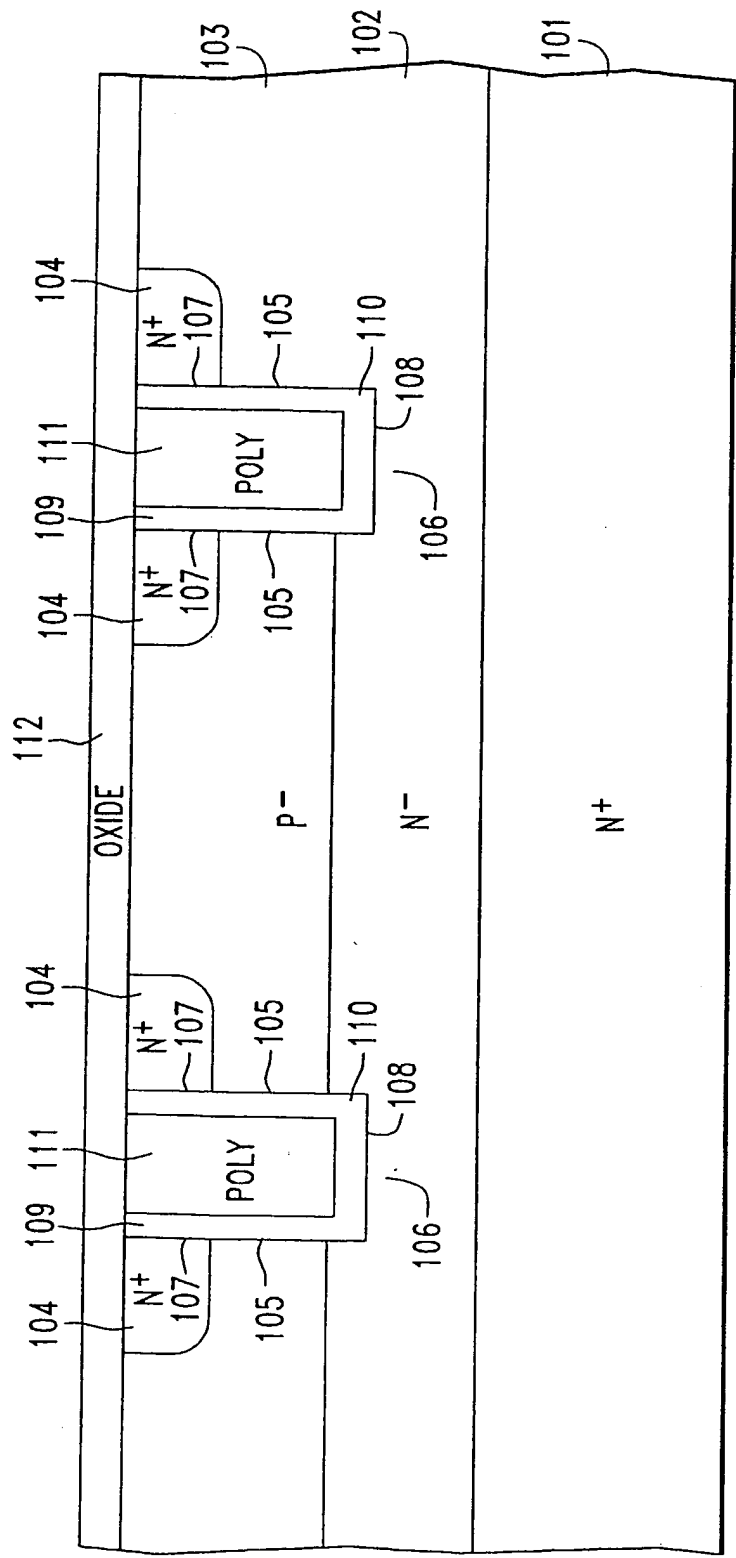


FIG. 1

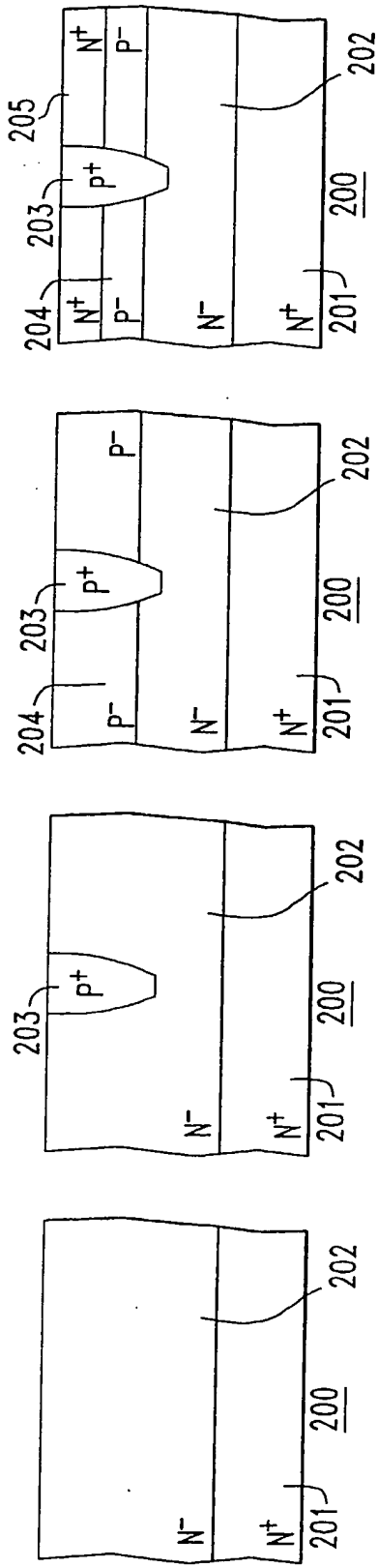


FIG. 2D

FIG. 2C

FIG. 2B

FIG. 2A

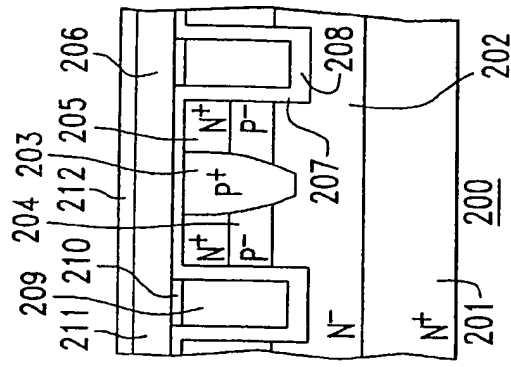


FIG. 2G

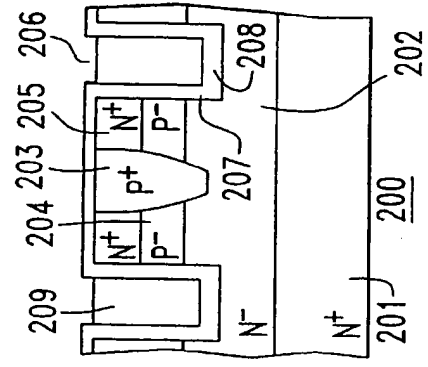


FIG. 2F

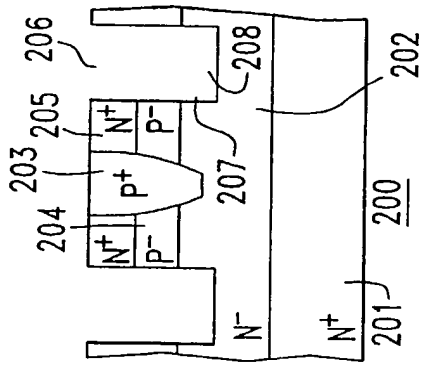


FIG. 2E

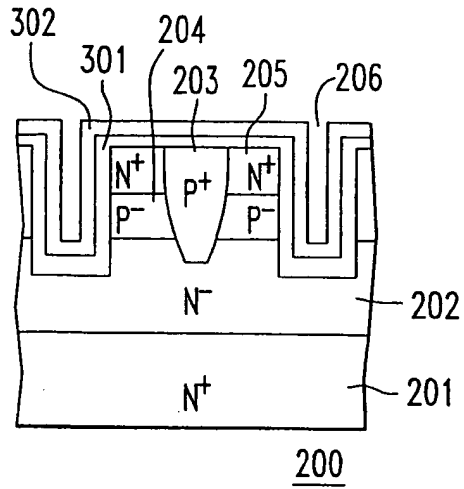


FIG. 3A

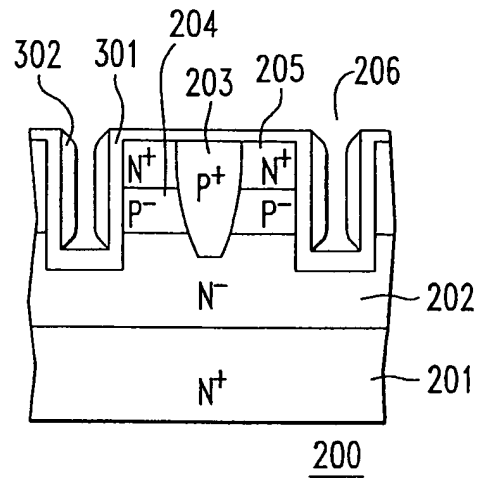


FIG. 3B

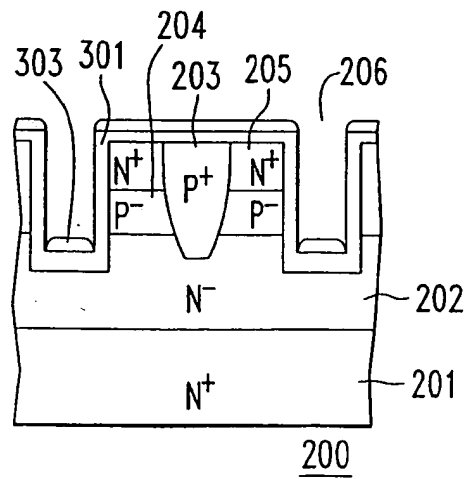


FIG. 3C

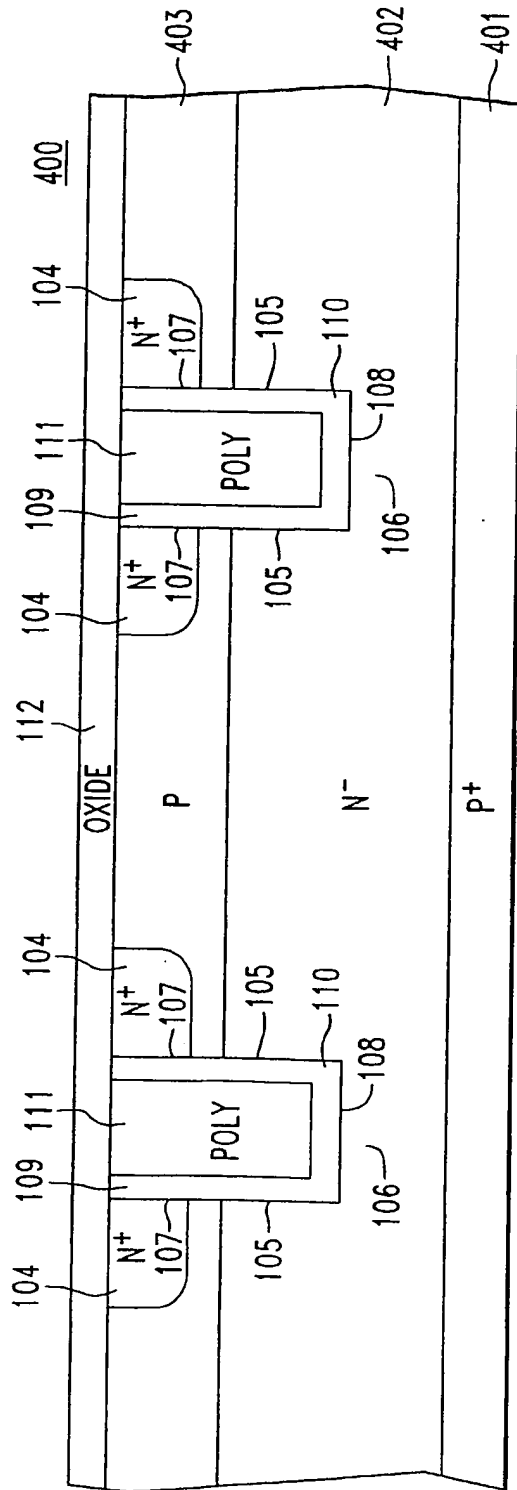


FIG. 4

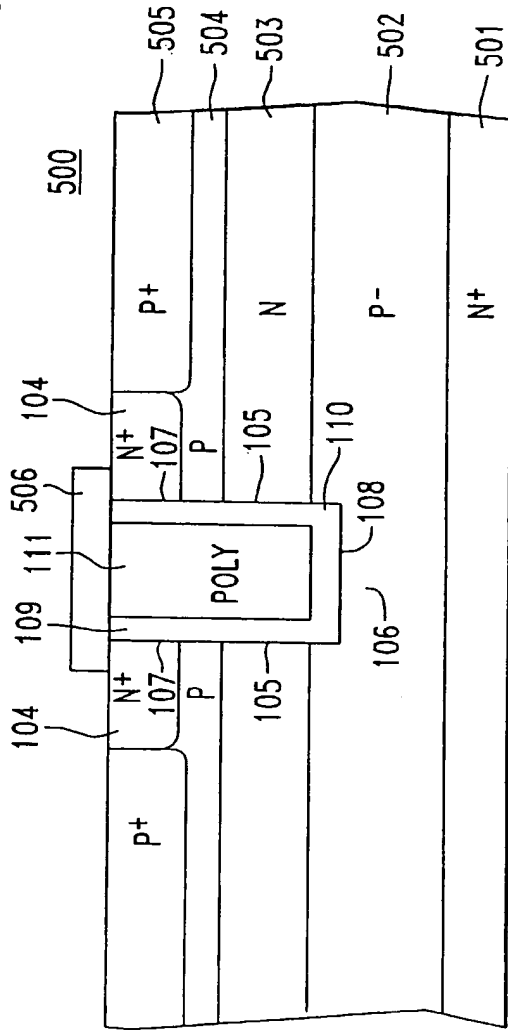


FIG. 5